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Modeling First Order Fire Effects

FINAL REPORT

Modelling First Order Fire Effects

by

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INTRODUCTION

Predicting direct effects of prescribed or natural fires can greatly help land managers develop reasonable management alternatives. Estimates of duff and fuel consumption, tree mortality, and smoke production and dispersal as a result of alternative fires can provide a quantitative means of evaluating management objectives. In addition, these first order fire effects can aid in predicting vegetal succession (Arno and others 1985). Currently there are theoretical and empirical means of assessing these direct, or first order, fire effects but they 1) are regionally specific, 2) are vegetation specific, 3) require inputs which may be unobtainable for the land manager, 4) limited to specific prefire moisture and fuel loading conditions, 5) are hidden in past research publications and not easily usable for the manager, and/or 6) may contain a great deal of variation (Brown and others 1985, Dryness and Norum 1983, Harrington 1987, Chrosciewicz 1978a,1978b, Blackhall and Auclair 1982). All equations, algorithms, and rules for calculating first order fire effects across the country badly need to be collected, organized, and made readily accessable to the land manager.

The purpose of this study was to develop a prototype first order fire effects computer model for use by land managers across the entire United States. This First Order Fire Effects Model (FOFEM) is to incorporate all pertinent research findings and personal observations of fire effects in a usable format. The model is a first attempt at a complete Expert System which would not only predict fire effects but prescribe possible management actions.

METHODS

This study's objective was to develop a computer program which would predict direct effects of fire on duff consumption, fuel consumption, and tree

mortality for any forest in the western United States. This was accomplished through the following steps:

1. Scanned research literature and collected all equations, observations, or algorithms that attempt to quantify first order fire effects.

2. Contacted research and management people concerned with first order fire effects and obtained any present or unpublished material that may aid in predicting fire effects.

3. Summarized all collected first order fire effects material and converted the summarized material to a format which allows direct comparison between research studies (See Appendix A). This involved graphing all equations and algorithms using compatible inputs and outputs so these equations may be directly comparible (see Appendix B).

4. Met with INT research personnel and decided the stratification and structure of FOFEM (March 89).

5. Presented INT research personnel with the results of fire effects summary (Step 3) (see Appendix C) and then decided which equations or algorithms were most appropriate for predicting fire effects. This involved three separate meetings because of the three effects specified in the study objective: 1) duff consumption (May 89), 2) woody fuel consumption (May 89), and 3) tree mortality (Sept. 89).

6. Identified weaknesses and strengths of selected equations and obtained measures of variation for the equations (see Appendix C).

7. Developed rules that dictate under which conditions a fire effects equation is used.

8. Integrated selected equations and rule bases into a computer program. Guidelines for program development were:

   a. Must be understandable to land managers who are not computer literate.
   b. Must be easily accessable to land managers. Therefore the final FOFEM program will be integrated in the ECOPAC software package distributed by the Northern Region's Ecosystem Management Program to all National Forest Ranger Districts.
   c. Must be compatible with USFS computer architecture (FSIA). Therefore FOFEM was programmed using the FSAT (Forest Service Applications Toolkit) utility for developing input screens compatible with CEO structure.
   d. Input and output must be presented both in a form for fire effects planning and prediction.
   e. Program must be written in a generally accepted computer language. It was decided to program the FOFEM prototype in FORTRAN 77 on the Data General minicomputer. Special consideration was given for adapting FOFEM to the microcomputer (PC) in the program development.

9. Debugged FOFEM and presented the draft version of the program to various INT and Northern Region personnel.

10. Incorporated comments and criticisms of program reviewers into FOFEM.

11. Added FOFEM to the ECOPAC software system.

RESULTS

The program FOFEM was written in FORTRAN 77 and contains approximately 6000 lines of computer code (Appendix D). It is implemented on the Data General minicomputer and is easily executed by the command --> X FOFEM. It was also added to ECOPAC (Keane and others 1988) and can be executed from this menu driven package. All FOFEM input entry screens have a corresponding HELP screen which explains, in detail, specific details of the input value required. FOFEM input values are classified in two categories, **required** or **optional**. Users are forced to enter required input data, but allowed to skip an optional field. FOFEM can print results of fire effects predictions to the terminal, a disk file, or the line printer. A HELP screen is also available for all results printed to the terminal. Any HELP screen can be obtained by depressing the HELP key (shift-F1). FOFEM was developed so it could directly access the ecological data base management system ECODATA and use ECODATA information as inputs to the model. The program was written so each input query is understandable and can be answered by the neophyte computer user. FOFEM executes quickly generating results in less than 10 seconds. All function keys on DG keyboard are defined for FOFEM as they are for CEO. The model's design allows efficient modification and/or addition of algorithms in the future.

Model Logic and Empirical Relationships

The model uses FSAT-structured input entry routines to query the user for values needed to compute first order fire effects. Once all input values are entered, the model then computes the fire effect prediction by first, keying to

the correct prediction equations, then using the keyed equation and user-input values to quantify the prediction. A detail discussion of the three first order fire effects algorithms implemented in FOFEM follows.

Duff Consumption

Equations to predict duff consumption are stratified by region (area of United States, see fig. 1), stand history, preburn duff depth, and tree cover type. The duff consumption algorithm provides estimation of 1) postburn duff depth reduction (cm), 2) postburn duff reduction (%), 3) exposed mineral soil (%). Each of these estimations can be computed from 1) lower duff moisture content (LDMC in %), 2) entire duff moisture content (EDMC in %), or 3) NFDRS 1000 hour fuel prediction (NFDRSTH in %), in this priority. For example, if the user did not enter the lower duff moisture content (LDMC), FOFEM would calculate the three duff consumption values from entire duff moisture content (EDMC). The following is a synthesis of the key used by FOFEM to decide the appropriate equation to use for predicting duff reduction. Equations are defined in Appendix E.

1. Sample stand in the Northern Rocky Mountains, Central Rocky Mountains, or the Southern Rocky Mountains (see Fig. 1).
    2. Stand has been clearcut.
        3. Preburn duff depth greater than 2.5 cm.
            Use following equations:

Duff reduction (cm)	LDMC	EQUATION 1
	EDMC	EQUATION 2
	NFDRSTH	EQUATION 3
Duff reduction (%)	LDMC	EQUATION 5
	EDMC	EQUATION 6
	NFDRSTH	EQUATION 7
Exposed mineral soil (%)	LDMC	EQUATION 9
	EDMC	EQUATION 10
	NFDRSTH	EQUATION 11

        3. Preburn duff depth less than 2.5 cm.
            Use following equations:

Duff reduction (cm)	LDMC	No equation avail
	EDMC	EQUATION 2
	NFDRSTH	EQUATION 3
Duff reduction (%)	LDMC	No equation avail

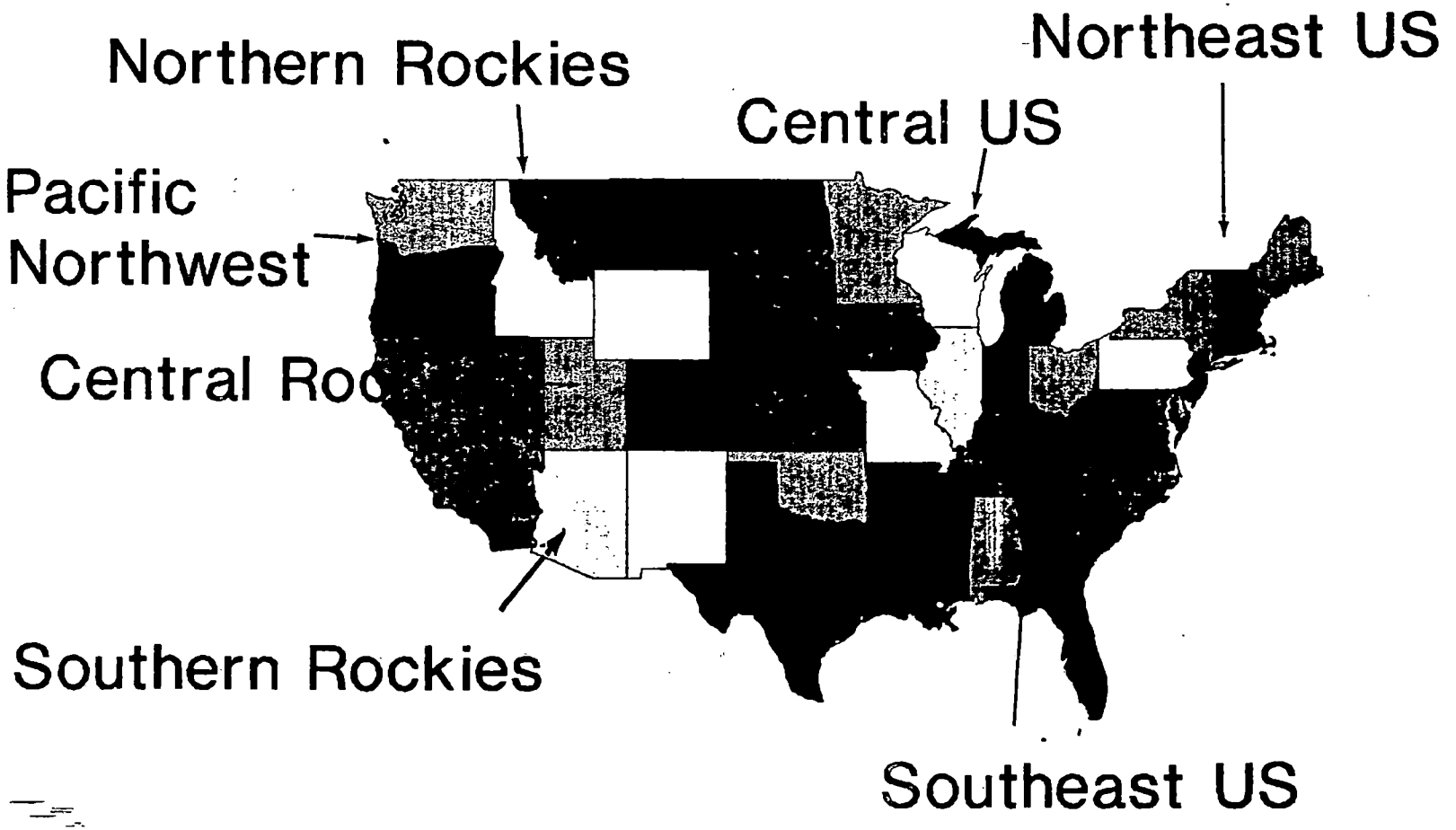

Figure 1. Region map for FOFEM program

	EDMC	EQUATION 6
	NFDRSTH	EQUATION 7
Exposed mineral soil (%)	LDMC	No equation avail
	EDMC	EQUATION 10
	NFDRSTH	EQUATION 14

2. Stand has NOT been clearcut.
   4. Stand contains greater than 40% Ponderosa Pine.
      5. Preburn duff depth greater than 2.5 cm.
         Use following equations:

Duff reduction (cm)	LDMC	EQUATION 4
	EDMC	No equ. avail
	NFDRSTH	No equ. avail
Duff reduction (%)	LDMC	EQUATION 8
	EDMC	No equ. avail
	NFDRSTH	No equ. avail
Exposed mineral soil (%)	LDMC	EQUATION 13
	EDMC	No equ. avail
	NFDRSTH	No equ. avail

      5. Preburn duff depth less than 2.5 cm.
         Use following equations:

Duff reduction (cm)	LDMC	No equ. avail
	EDMC	EQUATION 2
	NFDRSTH	EQUATION 3
Duff reduction (%)	LDMC	No equ. avail
	EDMC	EQUATION 6
	NFDRSTH	EQUATION 7
Exposed mineral soil (%)	LDMC	No equ. avail
	EDMC	EQUATION 10
	NFDRSTH	EQUATION 12

   4. Stand contains less than 40% Ponderosa Pine.
      6. Preburn duff depth greater than 2.5 cm.
         Use following equations:

Duff reduction (cm)	LDMC	EQUATION 1
	EDMC	EQUATION 2
	NFDRSTH	EQUATION 3
Duff reduction (%)	LDMC	EQUATION 5
	EDMC	EQUATION 6
	NFDRSTH	EQUATION 7
Exposed mineral soil (%)	LDMC	EQUATION 13
	EDMC	EQUATION 10
	NFDRSTH	EQUATION 14

      6. Preburn duff depth less than 2.5 cm.
         Use following equations:

Duff reduction (cm)	LDMC	No equ. avail
	EDMC	EQUATION 2
	NFDRSTH	EQUATION 3
Duff reduction (%)	LDMC	No equ. avail
	EDMC	EQUATION 6
	NFDRSTH	EQUATION 7
Exposed mineral soil (%)	LDMC	No equ. avail
	EDMC	EQUATION 10
	NFDRSTH	EQUATION 12

1. Sample stand in the Pacific Northwest (see Fig. 1).
   7. Stand in Douglas-fir zone.

8. Stand clearcut.
    9. Preburn duff depth greater than 2.5 cm.
        No equations available
    9. Preburn duff depth less than 2.5 cm.
        No equations available
8. Stand NOT clearcut (partial cut or untreated).
    10. Preburn duff depth greater than 2.5 cm.
        No equations available
    10. Preburn duff depth less than 2.5 cm.
        No equations available
7. Stand NOT in Douglas-fir zone.
    No equations are available
1. Sample stand in other parts of United States.
    No equations are available

All duff reduction predictions are presented with the equation used, equation reference, and a three measures of equation variablity (Coefficient of determination, number of observations, and standard deviation about regression).

Woody Fuel Consumption

Unfortunately, little attention was given to this routine because of the paucity of woody fuel consumption equations in the research literature. The equations implemented in FOFEM for the Northern, Central, and Southern Rocky Mountains are as follows with equation numbers corresponding to that in Appendix E.

1 hour timelag woody fuel size class ..... EQUATION 20
10 hour timelag woody fuel size class ..... EQUATION 21
100 hour timelag woody fuel size class ..... EQUATION 22
1000 hour timelag woody fuel size class ..... EQUATION 23

These are the only regions which have woody fuel consumption equations as yet.

Tree Mortality

The tree mortality routine uses the negative exponential probability function developed by Ryan and Reinhardt (1988) for all western tree species.

This equation (EQUATION 30 in Appendix E) is used for all species and diameter classes of trees in the Northern, Central, and Southern Rocky Mountains, and also the Pacific Northwest. The tree mortality routine allows the user to compute the probability of mortality for one tree, or simulate fire-caused mortality in a stand. Inputs for the individual tree mortality subroutine include 1) tree species - REQUIRED, 2) DBH (in) - REQUIRED, 3) height (ft) - OPTIONAL, 4) live crown ratio - OPTIONAL, and 5) scorch height (ft) - REQUIRED. Inputs for the simulated stand mortality routine are only 1) tree species and 2) DBH (in). The user can elect to obtain these values from ECODATA or the Timber Stand Data Base.

The stand fire mortality simulation routine computes number of trees killed by first calculating a probability of mortality for each tree. Then a random number is generated and if the calculated probability of mortality is greater than the random number the tree is killed. Outputs include preburn stand densities, postburn stand densities, densities of trees killed, average diameter killed, average probability of mortality and number trees killed. All densities are stratified by species and diameter classes.

DISCUSSION

There were many problems and limitations involved in developing a National First Order Fire Effects Model which were revealed as a result of this study. Some of the limitations encountered are:

1. Many areas of the country had no fuel consumption or tree mortality research studies to create usable equations. Granted some parts of the US are not involved in active burning and will probably never need FOFEM, but consideration should be given to wildfire events. Parts of the country which have poor representation in the literature include areas where research is limiting (such as tundra or alpine ecosystems), where fire events are infrequent (the mesic environments), and areas where fires have little residual effect (such as chaparral, deserts or grasslands).

2. The independent and dependent variables used to quantify fire effects were often incompatible across studies. For example, one study might look at reduction in duff loading while another might use reduction in duff depth.

3. Some equations are robust (cover wide range of conditions) while other equations were quite limited in their use or application area.

4. The definition of a variable differed across studies. For example, some studies considered the depth of duff to include the litter layer (Canadian) and others did not (American).

5. The closeness-of-fit or the accuracy of some of the equations is in doubt. Some equations evaluated had R-squares of less than 0.40 and standard deviations about the regression line greater than half the mean. Some variables used in equations make no biological or physical sense.

6. The conditions of sampling differed between studies. Some studies looked at duff reduction in the spring while others sampled in the fall.

7. Many independent variables used to predict a fire effect are impossible to measure before the burn.

8. No tests of extrapolation of equations to new regions.

CONCLUSIONS

The results of this prototype modelling effort indicate that a National First Order Fire Effects Model is possible and justified. It is recommended that the National FOFEM be:

1. programmed using artificial intellegence in a state-of-the-art Expert System;

2. implemented as a prediction AND management tool. Inputs and outputs should be interchangable. For instance, the user should be able to calculate the duff reduction at some duff moisture content, or calculate the duff moisture content needed to reduce duff depth below some threshold value;

3. developed for microcomputer and Data General computers;

4. developed with graphic and tabular capability;

5. programmed so modification and implementation of new research findings are easily accomplished.

Eventual refinement of the present FORTRAN version of FOFEM is recommended and at the very least, FOFEM should be modified so it is a fire planning package.

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Appendix A

Summary of duff reduction and tree mortality equations generated from literature search

DUFF REDUCTION EQUATIONS

EQUATION	AUTHOR	ENVIRONMENT
NORTHEASTERN U.S.		
$WD = \frac{0.1926*(1.418-DM)}{(0.1774 + DM)}$	Van Wagner (1972)	Eastern white pine
WD = -1.09 + (0.0473 * DMC)	Van Wagner (1972)	Jack, white red pine in Ontario
NORTH CENTRAL U.S.		
DRC = 0.824 + 0.1521*BUI	McCrae (1980)	Jack pine, Ont.
DRC = 0.588 + 0.1946*BUI	McCrae (1980)	Mixed jack pine
DRC = 0.853 + 0.0888*BUI	McCrae (1980)	Lowland spruce
DRC =-7.995 + 0.3244*BUI	McCrae (1980)	Upland spruce
DRC = 2.154 + 0.0651*BUI	McCrae (1980)	Balsam fir
LN(WD) = 6.0 - (1.49*LN(DM))	Weber et al. (1987)	Jack pine
EMS = 99.0 - (0.97*DM)	Weber et al. (1987)	Jack pine
DRC = 2.7832 - 0.0528*DMC	Chrosciewicz (1978)	J.pine Man. thin
DRC = 9.2221 - 0.0943*DMC	Chrosciewicz (1978)	J.pine Man. thick
DRC = 3.4174 - 0.0476*DMC	Chrosciewicz (1978)	J.pine Sas. thin
DRC = 4.0291 - 0.0415*DMC	Chrosciewicz (1978)	J.pine Sas. mod.
DRC = 5.2682 - 0.0143*DMC	Chrosciewicz (1978)	J.pine Sas. thick
DRP = 103.5116 - 1.1668*DMC	Chrosciewicz (1978)	J.pine Man. thin
DRP = 100.1037 - 0.3303*DMC	Chrosciewicz (1978)	J.pine Man. thick
DRP = 96.4592 - 1.2341*DMC	Chrosciewicz (1978)	J.pine Sas. thin
DRP = 93.2991 - 0.2450*DMC	Chrosciewicz (1978)	J.pine Sas. mod.
DRP = 88.0343 - 0.0152*DMC	Chrosciewicz (1978)	J.pine Sas. thick
DRI = 0.1277 + 0.0236*ADMC	Stocks & Walker (1972)	J.pine Ont. thick
DRC = 0.8173 + 0.0527*BUI	Stocks (1987)	J.pine Ont.
DRC = -3.638 + 1.035*PDDC + 0.047*BUI	Stocks (1987)	J.pine Ont.
WD = 0.0058 + 0.179*BUI	Stocks (1987)	J.pine Ont.
ALASKA		
DRC = -6.6 + 0.76*PDDC - 0.048*MM - 0.047*DM	Dryness & Norum (1983)	B.spruce, AK
DRP = 15.6 + 1.48*PDDC - 0.1*MM	Dryness & Norum (1983)	B.spruce, AK
DRC = -211.102 + 11.88976*DM	Viereck & Schandelmeir (1979)	Spruce, AK

DUFF REDUCTION EQUATIONS

EQUATION	AUTHOR	ENVIRONMENT
SOUTHWESTERN U.S.		
DRP = 37.37 - 0.75*DM + 21.19*PDDC	Harrington (1987)	P.Pine SE AZ
DRP = 141.68 - 0.72*DM - 0.03*TPA	Harrington (1987)	P.Pine SE AZ
SOUTHEASTERN U.S.		
WDW = 3.4958 + 0.3833*PDDW - 0.0237* (100.26*RD**0.3027) - 5.6025/ (100.26*RD**0.3027)	Hough (1978)	Slash pine- GA,NC
PACIFIC NORTHWEST U.S.		
WDW = 2.55 + 0.027*WLC	Muraro (1971)	Hemlock-cedar, BC
DRI = 0.537 + 0.057*LGCON	Ottmar et al (1985)	Doug-fir-hem, WA
DRI = 0.323 + 1.034*(DRED)**0.5	Ottmar et al (1985)	Doug-fir-hem, WA
DRC = 1.209 + 0.435*(PLLF/LMC) + 0.044*DAYS	Little et al. (1986)	Doug-fir-hem, OR
DRC = 1.295 + 1.659*(PLLF/LMC)	Little et al. (1986)	Doug-fir-hem, OR
DRC = 0.839 + 1.413*(DREDC**0.5)	Little et al. (1986)	Doug-fir-hem, OR
WDM = 14.70 + 6.980*(PLLF/LMC) + 0.065*DAYS	Little et al. (1986)	Doug-fir-hem, OR
WDM = 17.01 + 23.26*(PLLF/LMC)	Little et al. (1986)	Doug-fir-hem, OR
WDM = 16.19 + 17.41*(DREDC**0.5)	Little et al. (1986)	Doug-fir-hem, OR
EMS = 28.0 - 2.4*PDDC + 0.43*DAYS	Little et al. (1986)	Doug-fir-hem, OR
EMS = 93.1 - 36.9*PDDC	Amaranthus (1984)	Mixed Doug-fir OR
DRC = -0.16 + 1.76*(DREDC)**0.5	Sandberg (1980)	Doug-fir, WA & OR
DRC = 6.67 - 0.13*NEDRTH	Sandberg (1980)	Doug-fir, WA & OR
DRF = 110.0 - 2.54*NFDRTH	Sandberg (1980)	Doug-fir, WA & OR
DRP = 133.0 - 2.05*NFDRTH - 2.54* NFDRHU	Sandberg (1980)	Doug-fir, WA & OR
DRP = 12.6 - 2.46*NFDRTH - 2.33* DM	Sandberg (1980)	Doug-fir, WA & OR
EMS = 79.0 - 2.27*NFDRTH	Sandberg (1980)	Doug-fir, WA & OR
LN(EMS) = -0.08 + 2.12*LN(DRP)	Sandberg (1980)	Doug-fir, WA & OR
DRC = -28.74 + 0.75*PDDC + 2.78* LOG(DMC) + 9.63*LOG(DC)	Blackhall & Auclair (1982)	W.spruce,s.fir BC
DRP = -217.5201 + 30.6354*LOG(DMC) + 97.1532*LOG(DC)	Blackhall & Auclair (1982)	W.spruce,s.fir BC

DUFF REDUCTION EQUATIONS

EQUATION	AUTHOR	ENVIRONMENT
PACIFIC NORTHWEST U.S.		
DRP = -91.5215 + 81.1322*LOG(DC) - 17.3192*LOG(FFMC)	Blackhall & Auclair (1982)	W.spruce,s.fir BC
DRP = -154.489 + 3.973*PDDC + 83.5* LOG(DC) + 1.3835*LOG(FFM)	Blackhall & Auclair (1982)	W.spruce,s.fir BC
EMS = -42.575 + 1.1177*PDDC + 0.1185* DMC + 0.2174*DC	Blackhall & Auclair (1982)	W.spruce,s.fir BC
NORTHERN ROCKY MOUNTAINS U.S.		
DRP = 100.0 - 63.772*EXP(-((DM/220) - 1.0)**8.0)	Shearer (1976)	Larch-fir, MT
DRC = 1.03 + 0.773*PDDC + 0.0306*DM - 14.0*SHRUB + 12.5*HERB	Norum (1976)	Larch-fir, fall MT
DRP = 52.0 + 1.280*DM + 3.34* H1M - - 253.0*SHRUB + 612.0*HERB	Norum (1976)	Larch-fir, fall MT
DRC = -4.1528 - 0.0024*DM - 0.05021* BUI + 1.3144*(BI**0.5)	Beaufait et al. (1977)	Cedar-fir, MT
DRC = 2.238 - 0.0244*DM + 0.439*PDDC	Brown et al. (1985)	Doug-fir-larch MT
DRP = 83.7 - 0.426*DM	Brown et al. (1985)	Larch-fir MT
EMS = 167.4 - 31.6*LN(DM)	Brown et al. (1985)	Doug-fir-larch MT
DRC = -0.3408 + 0.7860*PDDC	Reinhardt et al.(1989)	Hem-fir slash ID
DRP = 59.6 - 0.346*DM + 2.782* DREDC	Reinhardt et al.(1989)	Hem-fir slash ID
EMS = -8.98 + 0.899*DRP	Reinhardt et al.(1989) Brown et al. (1985)	Hem-fir slash ID

DICTIONARY OF DEPENDENT AND INDEPENDENT VARIABLES IN DUFF REDUCTION EQUATIONS

DEPENDENT VARIABLES (Y-VARIABLES)

WD = Duff loading (kg/m^2)
DRC = Duff reduction in depth (cm)
DRI = Duff reduction in depth (in)
DRP = Duff reduction in percent (%)
EMS = Exposed mineral soil (%)
WDW = Duff loading (tons/acre)
WDM = Duff loading (megagrams/ha)

INDEPENDENT VARIABLES (X-VARIABLES)

DM = Average- entire duff moisture content (%)
DMC = Duff Moisture Code
ADMC = Adjusted Duff Moisture Code
PDDC = Preburn duff depth (cm)
PDDI = Preburn duff depth (in)
MM = Moss moisture content (%)
BUI = Buildup Index
TPA = Trees per acre
PDDW = Preburn duff weight (tons/acre)
WLC = Water loss (cc)
LGCON = Large fuel (3+ in) consumption (tons/acre)
DRED = Diameter reduction in large fuels (3+ in) (in)
PLLF = Preburn large fuel loading (megagram/ha)
LMC = Large fuel moisture content (%)
DAYS = Days since rain
DREDC = Diameter reduction in large fuels (cm)
NFDRTH = Computed NFDR 1000 hr fuel moisture
NFDRHU = Computed NFDR 100 hr fuel moisture
SHRUB = Preburn shrub loading (kg/square meter)
HERB = Preburn herbaceous loading (kg/sq m)
HM = One hour woody fuel moisture content (%)
BI = Burning Index
FFMC = Fine fuel moisture code
FFM = Fine fuel moisture content (%)

VIABLE TREE MORTALITY EQUATIONS

Bob Keane
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Equation Number	Author or Reference	Equation Form
1	Greene and Shilling (1987)	$P_m = 1/[1 + EXP(-(a + b_1(DGL) + b_2(MTE)))]$
2	Simard et al. (1987)	$C = a + b_1 Ln(DBH) + b_2 Ln(MCH) + b_3 Ln(MSH)$
3	Ryan et al. (1988)	$P_m = 1/[1 + EXP(-(a + b(DBH,CK,NDEAD,SH))]$
4	Peterson and Arbaugh (1986)	$P_m = 1-1/[1+EXP(-(a+b_1(CK)+b_2(BS,BCR,DT,ID))]$
5	Saveland (1982)	$P_m = 1-1/[1+EXP(-(a + b_1(DBH) + b_2(SH)))]$
6	Ryan and Reinhardt (1988)	$P_m = 1/[1+EXP(a+b_1 BT+b_2(1-e^{BT})+b_3 CK^2))]$
7	Spicer (1982)	$P_m = 1/[1+EXP(a + b_1(CK) + b_2(HT))]$
8	Kauffman and Martin (1986)	$P_m = (a + b_1 DC + b_2 DM + b_3 SMC) / 100.0$
9	Ryan (1982)	$P_m = (9.51 * (EXP(0.024 * CK)) / 100.0$
10	Peterson (1983)	$P_m = 1-1/[1+EXP(a + b_1(CK) + b_2(BT))]$
11	VanWagendonk (1983)	$P_m = 0.5$ when $HT = a * FL^b$
12	Loomis (1973)	$P_m = a + b_1 HBB + b_2 DBH$
13	Bevins (1980)	$P_m = 1/[1+EXP(a + b_1(DBH) + b_2(SH))]$
14	Harmon (1984)	$Ln(P_m) = Ln(a) - b_1(BT)$
15	Brown and DeByle (1987)	$P_m = 1/[1+EXP(a + b_1(DBH) + b_2(CH,UCH,CC))]$

Equation Number	Tree Species	Ecosystem or Sampling area and type of forest	Number of Samp. trees
1	Loblolly pine Water Oak Sweet gum	Louisiana southern pine forest -- consisted mostly of loblolly pine and used a low intensity backfire	600
2	Aspen, Birch Maple, Oak	Wisconson hardwood forests -- looked at hardwood mortality after spring burns	748
3	Douglas-fir	Lubrecht State Forest -- PSME/VAGL h.t. -- burned with strip head fires	166
4	Douglas-fir Lodgepole pine	Sampled large burned-over areas (wildfire) in MT, ID, WY during 1981.	545
5	Ponderosa pine Douglas-fir	PSME/PHMA h.t. in Northern Idaho -- mixed pine with rare fir. All types fires	194
6	Spruce, fir Doug-fir, all species	Aggregated tree data from 43 fires in ID, MT, OR, WA. Fires were all types	2356
7	Douglas-fir	Larch-fir forest of north ID, seedtree fire	135
8	Shrub and Hardwoods	Ponderosa pine forests of the Sierra Nevada range of CA, early spring and early fall fire	45
9	Douglas-fir	fir-pine on Superior RD, Lolo NF,Montana	N/A
10	Douglas-fir Lodgepole,larch	Data taken from Norum Lubrecht study, MT	220
11	Sugar,ponder-osa, cedar,fir	All types of prescrib. fires in Yosimite Nat. Park, Sierra Nevada, CA	1087
12	4 spp Oak	Oak-Hickory forests of the southeast US	1308
13	Douglas-fir	Larch-fir forest -- Norum Lubrecht data	176
14	Maple,Pine	Fire survival southern applanchian hardwoods	44
15	Aspen	Southern ID, WY aspen stands -- prescribed and wildfires	1100

Equation Number	Range of X_1 Variable	Range of X_2 Variable	Range of X_3 Variable
1	DGL: 20-60 mm	MTE: 0-60000 C-Sec	
2	DBH: 3-20 in	MSH: 0.5-1.2 ft	MCH: 0.31-0.74 ft
3	DBH,CK,NDEAD,SH: N/A		
4	CK: 20-80%	BS:50-100%,BCR:0-0.8,BT:0.9-2.6cm,ID:0-1	
5	DBH: 7-70 cm	SH: 1-26 m	
6	BT: 0.0-10.8 cm	CK: 0-100%	
7	CK: 0-100%	HT: 54-133 ft	
8	DC: 11-94 t/a	DM: 5-120%	SMC: 3-58%
9	CK: 0-100%		
10	CK: 0-100%	BT: 0.1-9.0 cm	
11	N/A	N/A	
12	HBB: 0-34 ft	DBH: 1-22 in	
13	DBH: 5-19 in	SH: 0-70 ft	
14	N/A	N/A	
15	DBH: cm	CH: 9-116 cm,UCH:11-152,CC:0-100	

KEY TO VARIABLE SYMBOLS

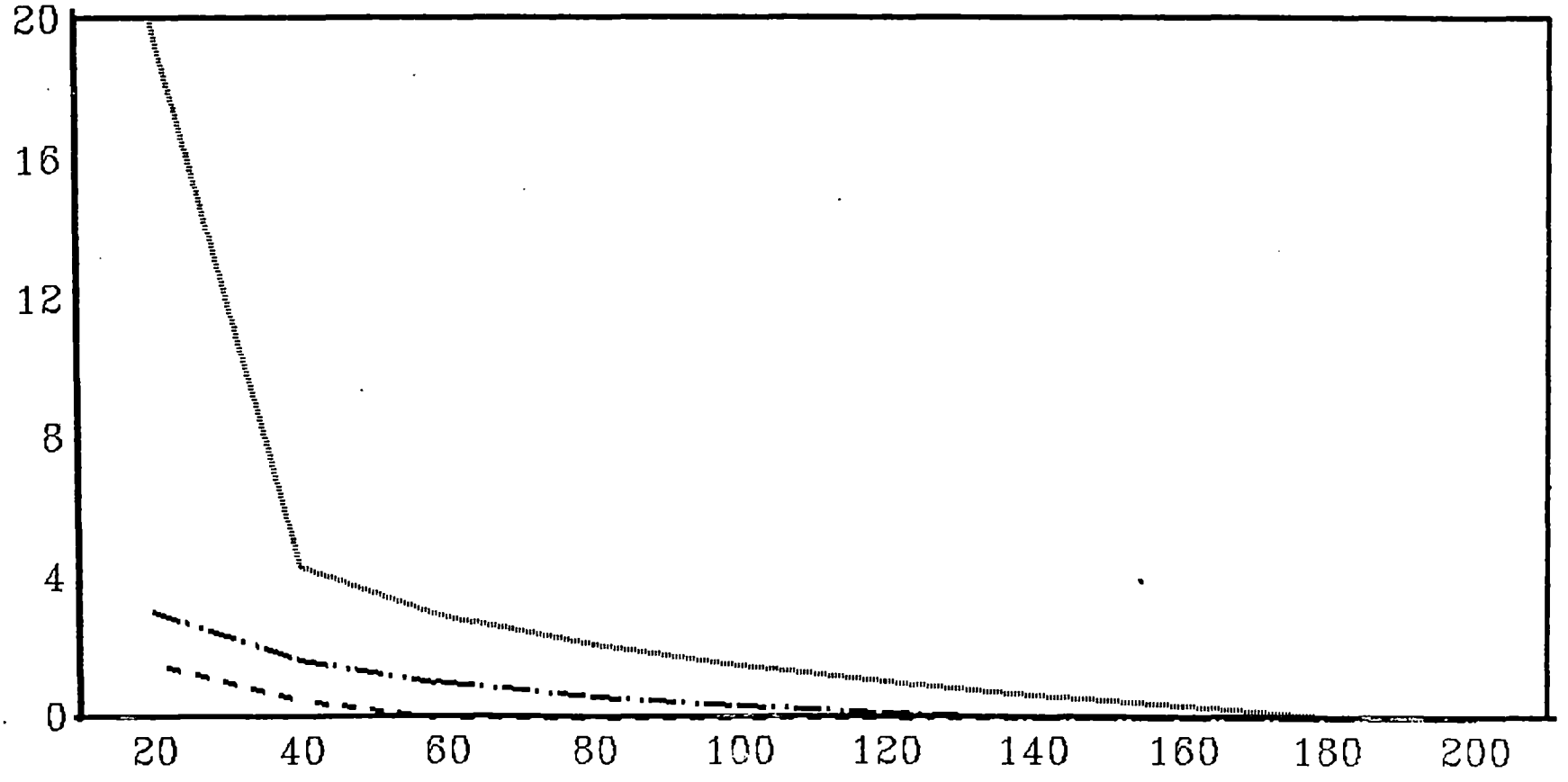
Symbol or Name	Description of variable
P_m	Probability of mortality (number between 0 and 1)
DGL	Diameter at ground line (mm)
MTE	Mean time exposure (degrees C - seconds)
DBH	Diameter breast height (cm or in)
C	Percent of circumference killed (%)
MSH	Minimum scorch height (ft)
MCH	Maximum char height (ft)
CK	Percent volume of live crown killed (%)
NDEAD	Number dead quadrants of cambiam
SH	Scorch height (ft)
BS	Percent of basal circumference scorched (%)
BCR	Bark char ratio
BT	Bark thickness at DBH (cm)
ID	Insect damage (0 or 1)
HT	Tree height (ft)
DC	Duff consumption (metric tons/ha)
DM	Duff moisture content (%)
SMC	Soil moisture content (%)
FL	Flame length (in)
HBB	Height of bole blackening (0.1 foot)
CH	Char height (cm)
UCH	Uphill char height (cm)
CC	Circumference charred (%)

Appendix B

Examples of graphic representation of duff reduction equation comparisons

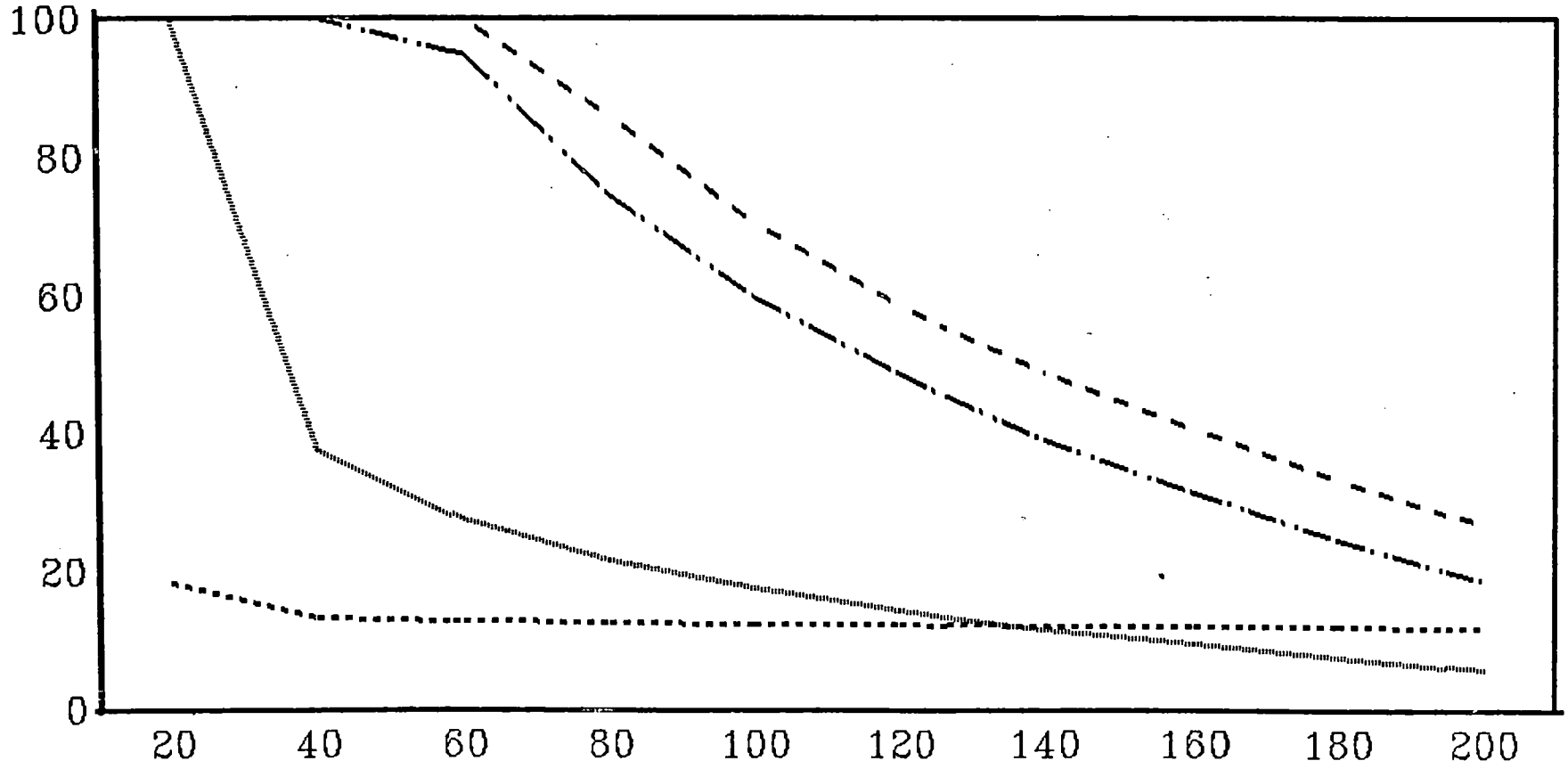
DUFF WEIGHT CONSUMPTION

DUFF CONSUMED (KG/SQ M) BY MOISTURE CONTENT (%)



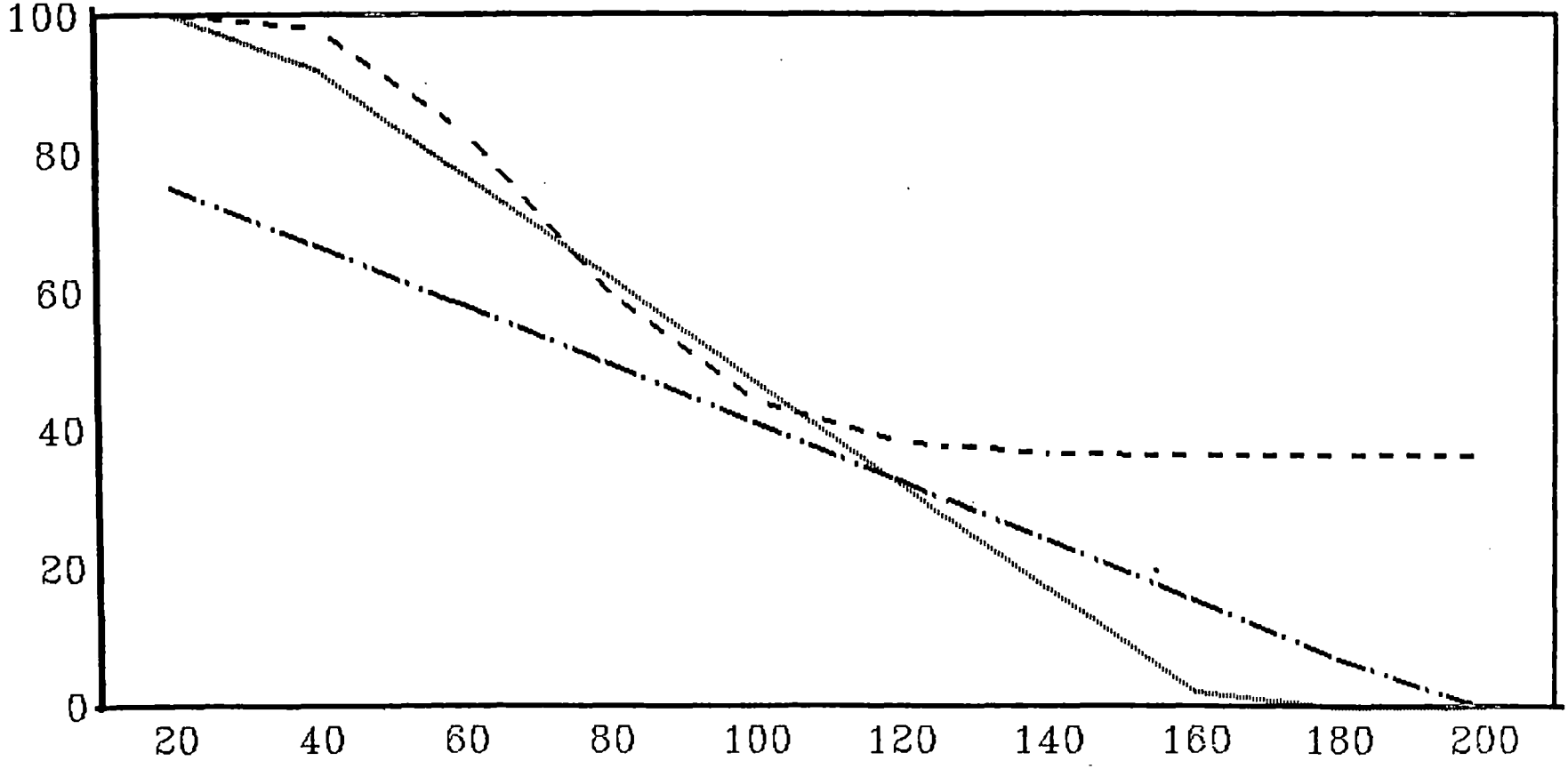
DUFF CONSUMPTION

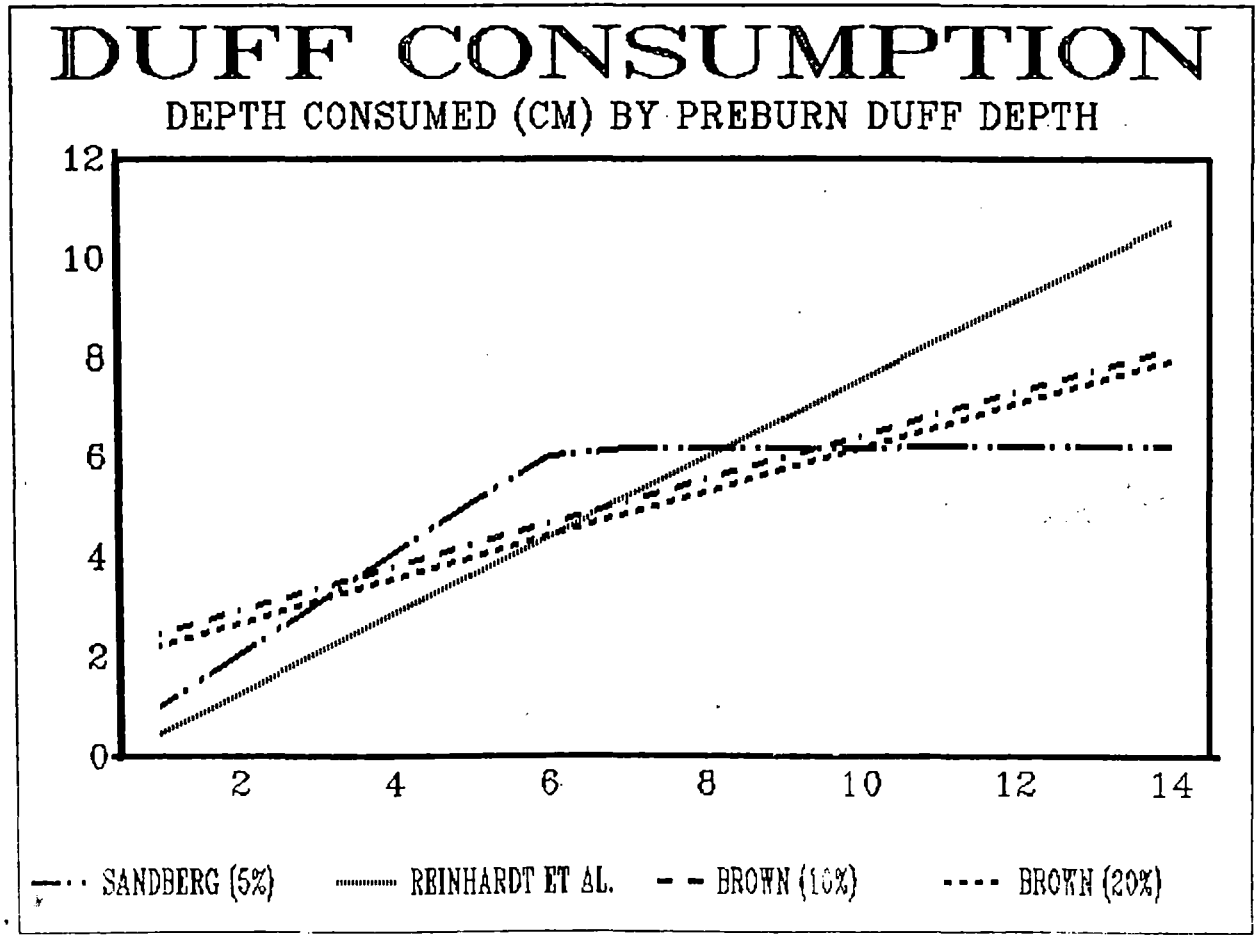
PERCENT CONSUMED (%) BY DUFF MOISTURE (%)



DUFF CONSUMPTION

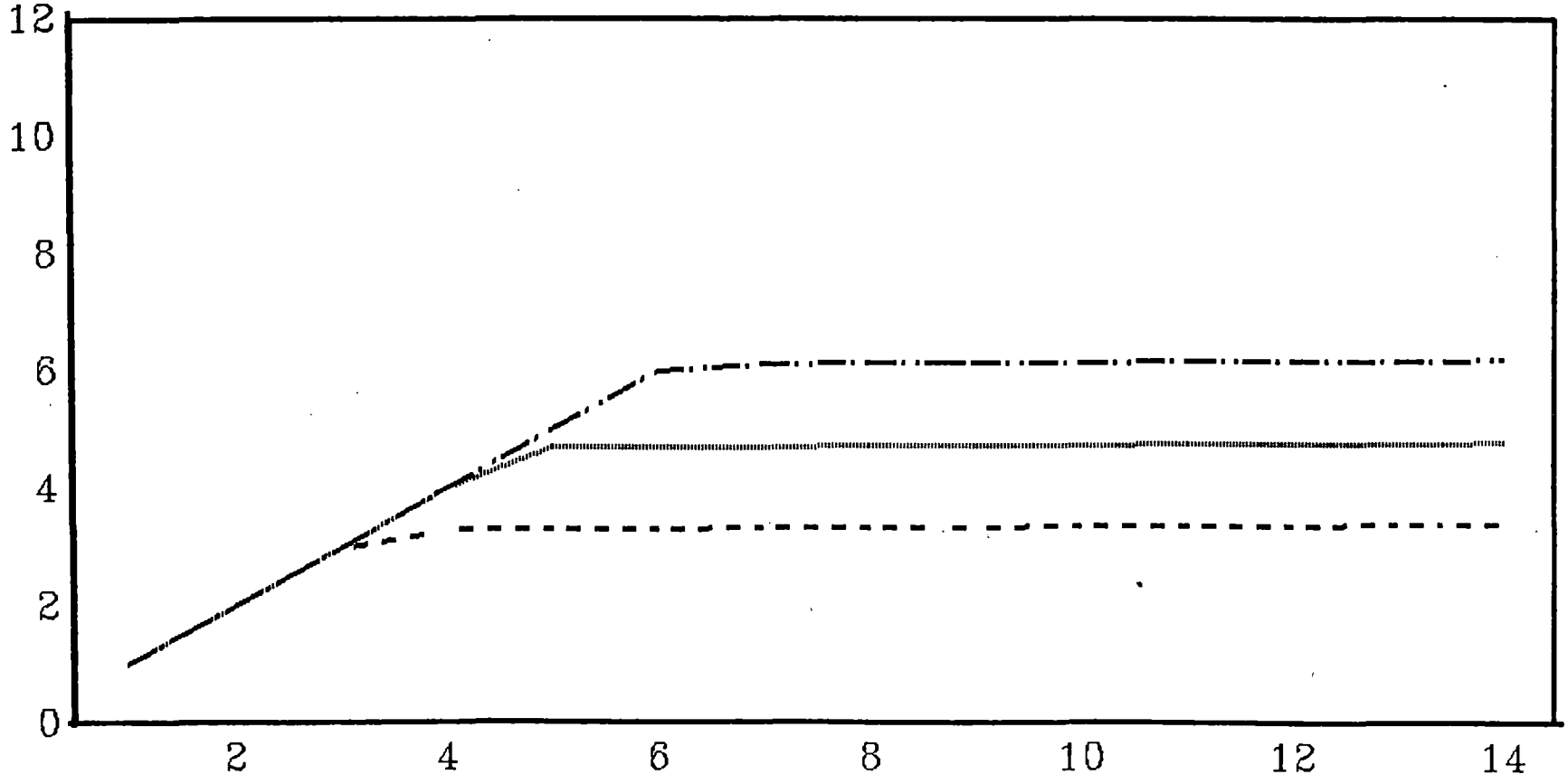
PERCENT CONSUMED (%) BY DUFF MOISTURE (%)




DUFF CONSUMPTION
DEPTH CONSUMED (CM) BY PREBURN DUFF DEPTH
12
10
8
6
4
2
0
2
4
6
8
10
12
14
SANDBERG (5%)
REINHARDT ET AL.
BROWN (10%)
BROWN (20%)

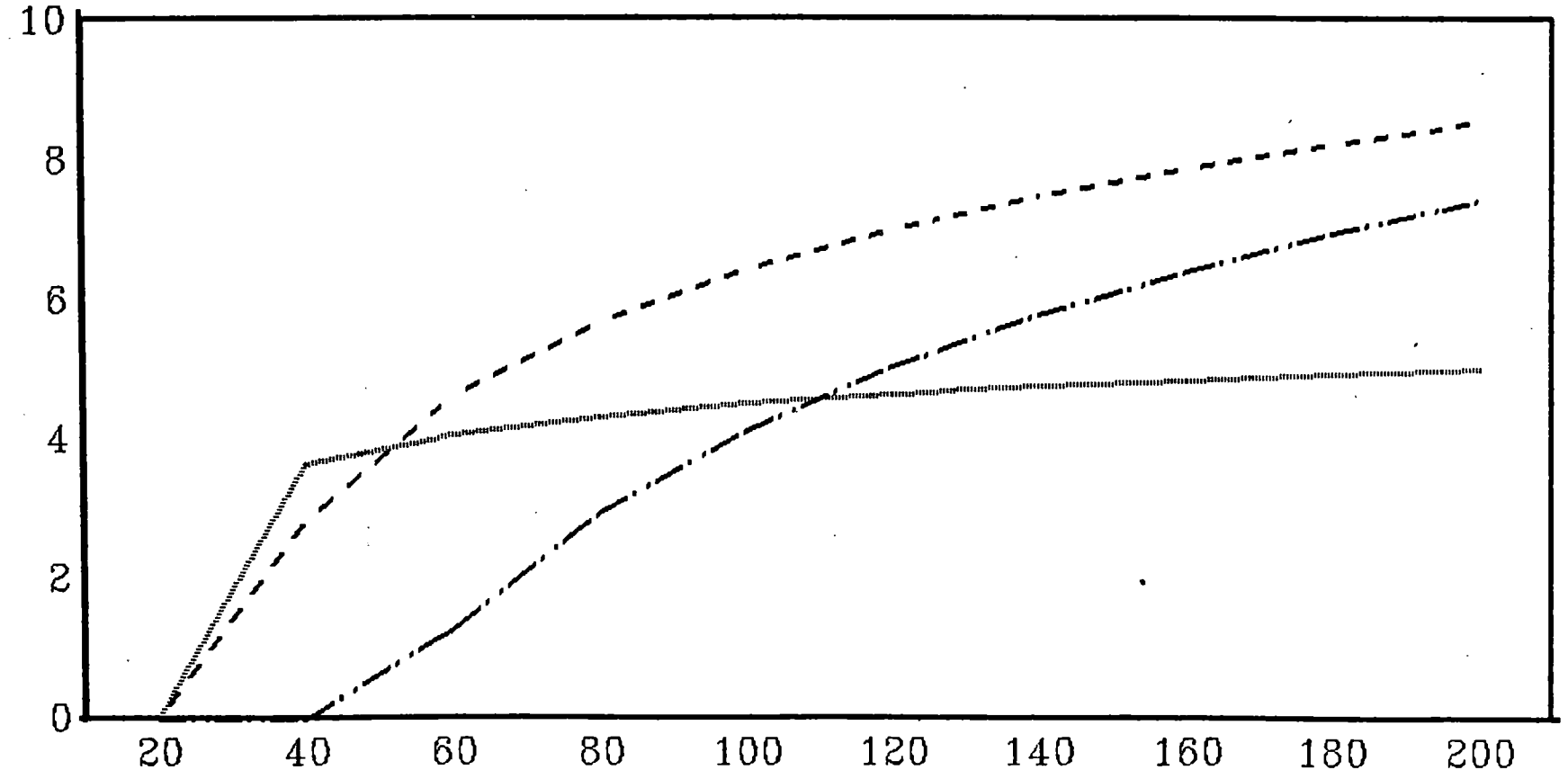
DUFF CONSUMPTION

DUFF DEPTH CONSUMED (CM) BY PREBURN DUFF DEPTH (CM)



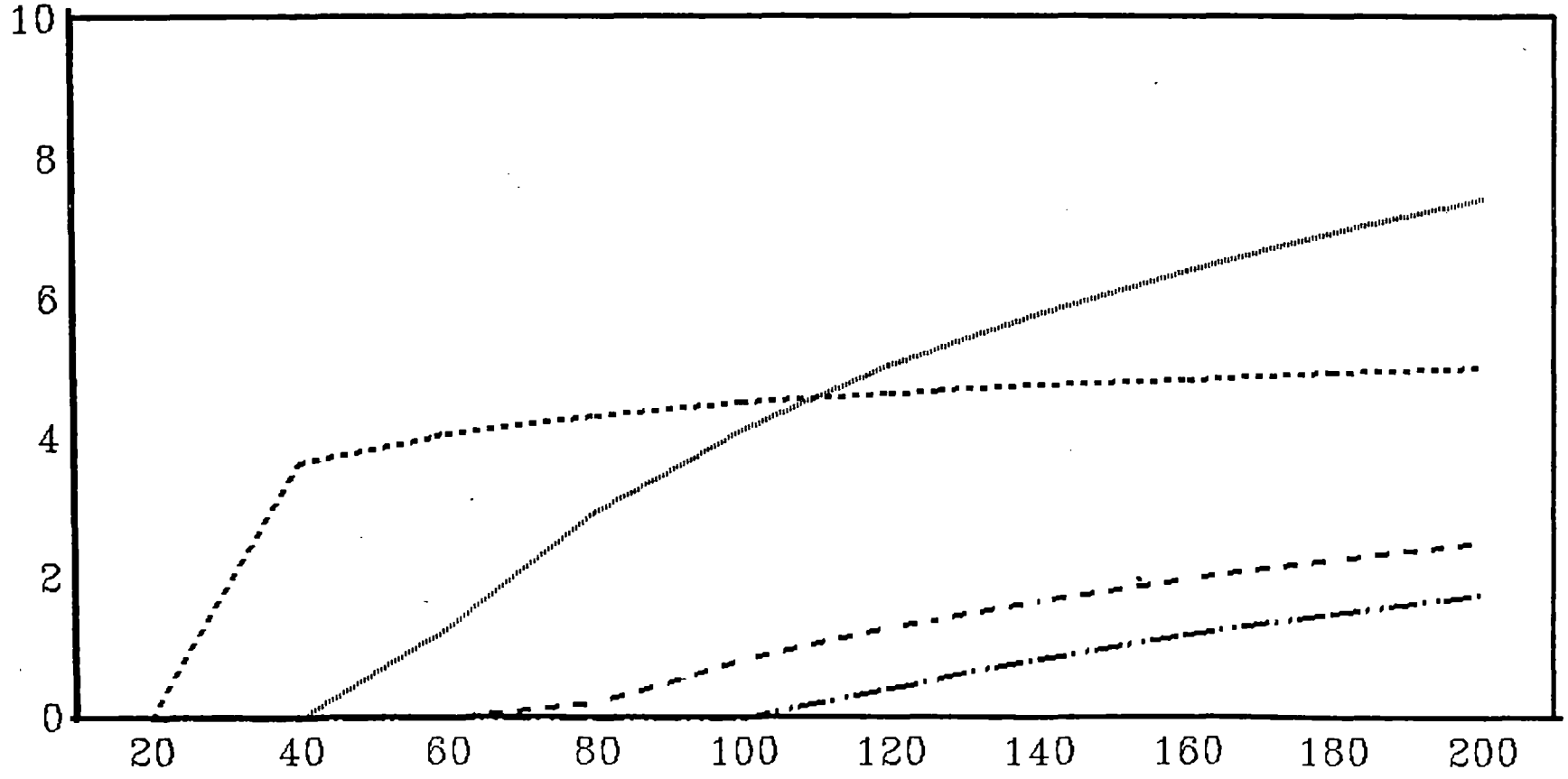
DUFF REMAINING

DUFF DEPTH AFTER FIRE (CM) BY DUFF MOISTURE (%)

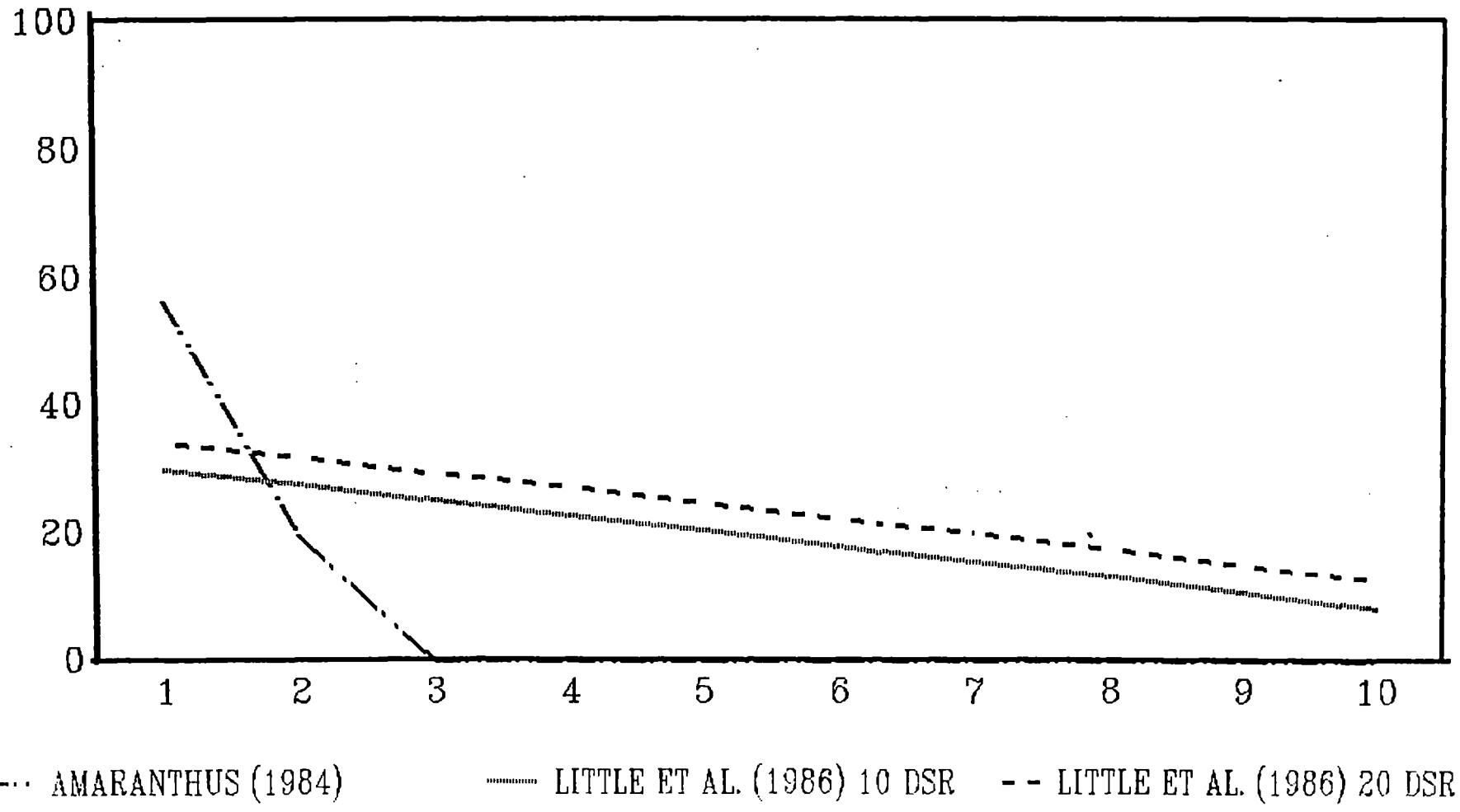


DUFF REMAINING

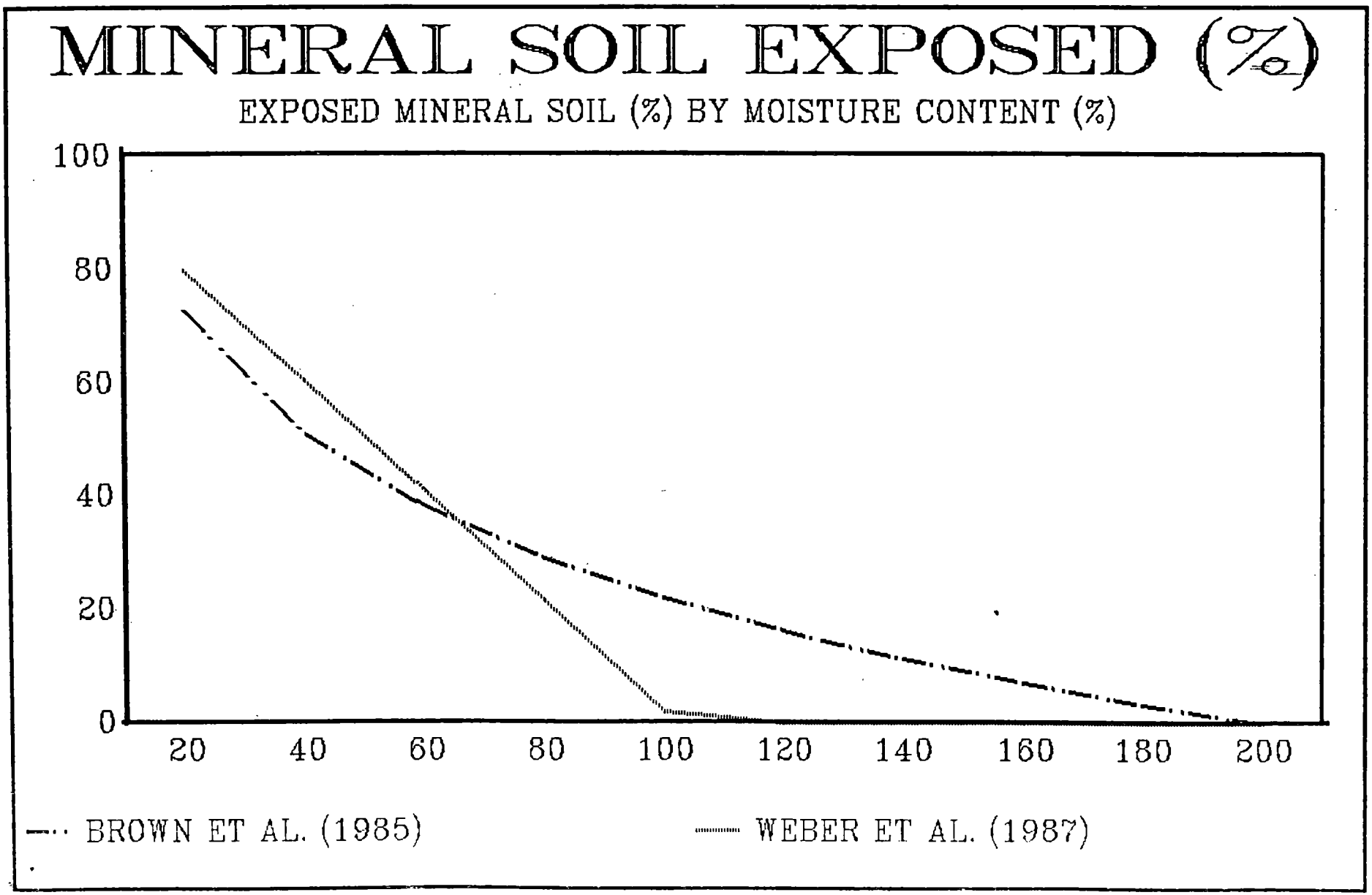
DUFF DEPTH AFTER FIRE (CM) BY DUFF MOISTURE (%)



MINERAL SOIL EXPOSED (%)



MINERAL SOIL EXPOSED (%)



Appendix C

Descriptions of equation development as a model building aid

Appendix D

Computer code for FOFUM

The listing is available on request to Bob Keane or Jim Brown at the Intermountain Fire Sciences Laboratory, P.O. Box 8089, Missoula, MT 59807.

DUFF REDUCTION EQUATION SUMMARY

REGION: Northern Rocky Mountains

AUTHOR: **Brown et al. (1985)**

ENVIRONMENT: This paper analyzes data collected from three sites in three separate studies: 1) Miller-Newman, 2) Lubrecht, and 3) Northern Idaho. These sites are more or less accounted for in other studys presented later. Miller-Newman was mostly western larch-Douglas-fir forests in ABGR, THPL and TSHE series habitat types. Slopes were 9-76% in 4200-5400 ft MSL. Lubrecht was larch-fir forests in the PSME and ABLA series habitat types. Stands were 4800 ft on 20 to 50% slopes. Northern Idaho stands were dry Ponderosa pine and Douglas-fir forests on 0-30% slopes between 2600 and 2900 ft MSL. All data mostly collected in Douglas-fir or P.Pine cover type.

STAND HISTORY: Miller-Newman site was clearcut and burned with logging slash. Slashing and directional felling were done to maintain fuel continuity. Lubrecht was an uncut stand of Douglas-fir with natural fuels. Northern Idaho was done in selectively logged seral Ponderosa pine stands followed by mechanical piling.

BURNING DETAILS: Miller-Newman site was burned in May thru Oct. using single headfires. Fine fuel moisture contents were between 6 and 21%. Lubrecht site was burned with a strip headfire when fine fuel moistures were 9-35% in the months of May thru Oct. N.Idaho sites were burned only in the fall with strip and single headfires and backfires while the fine fuel moistures were 9-21%.

RANGE OF THE DATA: The following table explains the range of data in the more important variables.

Variable Name	Ranges		
	Miller-Newman	Lubrecht	Northern Idaho
Duff reduction (%) DRP	1 - 100	14 - 73	0 - 56
Duff red. (cm) DRC	0 - 6	1 - 8	0 - 3
Min. soil exp. (%) EMS	0 - 93	0 - 51	N/A
Pre. duff depth (cm) PDDC	0.3 - 8	4 - 11	1 - 7
Duff moist. (%) DM	30 - 221	16 - 106	9 - 46
NFDR-1000 (%) NFDRTH	7 - 25	11 - 18	17 - 20
Duff moist code DMC	13 - 249	26 - 162	33 - 119

COMMENTS: Selection of data to enter into analysis done by authors. Some data were excluded from the construction of various equations at the discretion of the authors. Validated with some of Sandberg's (1980) equations with little success. Other validation data (from the region) agreed well with equations.

AUTHOR: **Shearer (1975)**

ENVIRONMENT: Data collected from the Miller Creek and Martin Creek drainages on the Flathead N.F. Overstory stand composed of western larch, Engelmann

spruce and Douglas-fir in equal proportions. Most of the area is ABLA/PAMY h.t. with MEFE and XETE phases. Slopes were moderately steep (10-50%) on all aspects in 4200-5000 ft elevation. Soil is argillite and quartzite glacial till.

STAND HISTORY: Stands were clearcut with skidder or tractors. After logging most units were broadcast burned within a year after cutting. Preharvest stand age was 200-250 years. Fuels were slashed and trees were felled to achieve spacial uniformity across the fuelbed.

BURNING DETAILS: Units were burned in May thru Oct. using single headfires set by drip torches, blivet lines and flamethrowers. Fine fuel moisture contents were between 6 and 21%.

RANGE OF THE DATA: Duff reduction (%) DRP ranged from 0 to 100%, Duff moisture content ranged from 50-200%, duff depths ranged from 0 to 18.0 cm. Equations derived from 20 observations.

COMMENTS: Used Matchacurve to get a sigmoid curve with asymtopes at 100 and 40% duff reductions. To use Matchacurve you must know the upper limit of moisture content - Shearer assumed 220%.

AUTHOR: **Reinhardt et al. (1989)**

ENVIRONMENT: Data collected on Deception Cr. Exp. Forest near Coeur d'Alene, Idaho. Site was a series of small logging units on steep north-facing slopes at 3000-4000 ft elevation. Site was in the white pine cover type and the TSHE/CLUN h.t. Dominant trees were grand fir, white pine and western hemlock. Precipitation ranges around 56 in/yr.

STAND HISTORY: Stands were clearcut and seed tree cut with tractor and YUM methods. Unmerchantable were cut and somewhat removed. Preharvest stands were mature seral communities previously selectively cut earlier this century. Stands were 120-200+ years 35MBF/acre.

BURNING DETAILS: Units were burned in late spring, late summer and fall using strip headfires lit by propane torches.

RANGE OF THE DATA: Duff reduction (cm) DRC ranged from 1 to 13 cm, Duff moisture content ranged from 58-300%, duff depths ranged from 2 to 13 cm. Equations derived from 35 observations.

COMMENTS: Data from a limited range of vegetation conditions. Burns were complete. A comparison between other reduction equations is offered.

AUTHOR: **Norum (1976)**

ENVIRONMENT: Data collected on Lubrecht Exp. Forest near Ovando, MT. Site burned was a mature stand of Douglas-fir and western larch with moderate slope

(20-50%) on east and northeast exposures at 4800 feet elevation. Overstory trees were probably 80-100 years old.

STAND HISTORY: This stand was probably second growth of larch-fir-lodgepole pine. Fuels averaged 8.5 to 35.0 tons/acre before the burn. This study also looked at woody fuel consumption and tree mortality.

BURNING DETAILS: This site was prescribed burned in spring and fall with fine fuel moistures at 8-35%. The fuels burned were natural fuels and were ignited alnog a contour with a drip torch.

RANGE OF THE DATA: Percent duff reduction (%) DRP ranged from 14-72%. Duff moisture contents ranged from 23-145%, while duff depths ranged from 4 to 11 cm. Equations derived from 20 observations.

COMMENTS: Data from a limited range of vegetation and site conditions. First stratification of data (spring/fall burn) divided the data set into two very small groups which might be too small for proper analysis. Regression analysis yielded equations with many independent variables further limiting the range of application.

AUTHOR: **Beaufait et al. (1977)**

ENVIRONMENT: These data are the data collected from the Miller Creek and Newman Ridge sites on the Lolo and Flathead N.F. Overstory stand composed of western larch, Engelmann spruce and Douglas-fir in equal proportions. Most of the area is ABLA/PAMY h.t. with MEFE and XETE phases. Slopes were moderately steep (10-50%) on all aspects in 4200-5000 ft elevation. Soil is argillite and quartzite glacial till.

STAND HISTORY: Stands were clearcut with skidder or tractors. After logging most units were broadcast burned within a year after cutting. Preharvest stand age was 200-250 years. Fuels were slashed and trees were felled to achieve spacial uniformity across the fuelbed.

BURNING DETAILS: Units were burned in May thru Oct. using single headfires set by drip torches, blivet lines and flamethrowers. Fine fuel moisture contents were between 6 and 21%.

RANGE OF THE DATA: Duff reduction (cm) DRC ranged from 0 to 6 cm. Duff moisture content ranged from 7-99%, duff depths ranged from 0 to 18.0 cm. Equations derived from 64 observations.

COMMENTS: Used REX software to get a multiple regression equation which also contains the variable BUI (buildup index) and a transformation of BUI. High significance for the regression equation.

DUFF REDUCTION EQUATION SUMMARY

REGION: North Central U.S.

AUTHOR: **McCrae (1980)**

ENVIRONMENT: Data was collected in 1977-78 at five different stands in Ontario. The cover types of the five stands were: 1) Jack Pine, 2) Jack Pine Mixedwood, 3) Lowland Black Spruce, 4) Upland Spruce and 5) Balsam Fir. This study also evaluated the reduction of slash fuels using prescribed fire.

STAND HISTORY: Stands were clearcut and logs were removed with tractor skidders. No treatment to the fuels is mentioned. Fuel loading of slash ran from 0-10 kg/square meter.

BURNING DETAILS: No information was given as to the quality and timing of the broadcast burn.

RANGE OF THE DATA: Duff reduction (cm) DRC ranged from 0.0 to 9.2 cm. Range in the independent variable BUI was 7-61. Number of observations were 1) 24, 2) 46, 3) 25, 4) 8, and 5) 6.

COMMENTS: The variable BUI is not used in the U.S. for characterizing weather conditions. There is a great deal of data in this study. One thing the author did not do is combine the data to achieve a more robust equations instead of stratifying the data by cover type.

AUTHOR: **Weber et al. (1987)**

ENVIRONMENT: Study site was on the Petawawa National Forestry Institute in Ontario, Canada. Soils are Precambrian granite and gneiss, well drained with weak soil development. Sampling site is an evenaged Jack pine stand on moderate slope and aspect. A nearly continuous mat of feather moss was present underneath the forest canopy. Other shrubs included Vaccinium myrtilloides and Gau;ltheria procumbens with some Pteridium aquilinum. As far as I know these stands were NOT logged prior to burning and never were logged.

STAND HISTORY: The evenaged Jack pine stand originated from a wildfire in 1915. Current tree basal area is 26 square meters/hectare, with a density of 2000 trees/hectare.

BURNING DETAILS: The study sites were prescribed burned using strip headfires set along site boundries. These fires were set in May through August. There is also one wildfire which was includes. This fire was set in May. Intensites ran from 70-17000 kW/m with spread rates of 0.4 to 24 m/min.

RANGE OF THE DATA: Duff reduction by weight (%) ranged from 11-82%. Duff moistures ran from 35-105% and preburn duff weights went from 2.8-4.0 kg/sq. meter. Exposed mineral soil ranged from 0-78%. There were 7 observations.

COMMENTS: Duff reduction is presented by weight not depth and this may not be useful. Exposed mineral soil equations are good but are only a result of seven observations. There is also regression equations for tree mortality in this paper.

AUTHOR: **Chrosciewicz (1978a & 1978b)**

ENVIRONMENT: These two studies were done in central Saskatchewan and southwestern Manitoba. These sites were flat clearcut stands of Jack pine on deep loamy stony tills. Stands were moderately moist and contained Jack pine with some Black Spruce and widely scattered tamarack and aspen. Understory vegetation was 0.5 meter tall shrubs and grasses with some sites containing feather mosses. Moss cover ranged from 40-90%.

STAND HISTORY: Stands were clearcut and tractor hauled. Original stands were 70-80 years old with basal areas of 21-31 sq.m/ha.

BURNING DETAILS: The clearcuts were broadcast burned from June through October using U-shaped backfires completed by a headfire.

RANGE OF THE DATA: Preburn duff depths ranged from 1.6 to 12.4 cm. Preburn duff moisture contents went from 58-282%. Duff reduction (cm) DRC went from 0-4 cm. Number of observations ranges from 7-24.

COMMENTS: Most equations had very bad fits to least squared regression. The data were subjectively stratified by duff deepness (thin, mod. thick, and thick duff types) before preforming regression analysis. Regression equations extremely difficult to understand. No attempt was made to combine the Manitoba data with the Saskatchwan data for regression analysis.

AUTHOR: **Stocks and Walker (1972)**

ENVIRONMENT: Jack pine stands in Northeastern Ontario Canada. These sites are flat, well drained soils containing jack pine and black spruce. These stands WERE logged in the winter.

STAND HISTORY: Stands were 55-80 years old with 158-180 sq.ft./acre basal area. Stands were cut in 1969 for pulp and there were no slash treatments.

BURNING DETAILS: All units were broadcast burned probably using strip headfires. Fires had rates of spread from 0.2-2.1 ft/sec and intensities of 473-17000 BTU/sec/ft.

RANGE OF THE DATA: Preburn duff depths ran from 4-11 cm. Duff moisture codes went from 9-25. Depth of burn ranged from 1-4 cm. Regression equations derived from 25 observations.

COMMENTS: Data from a limited range of vegetation and site conditions. Study also includes slash fuel consumption. Equations are good and fits are acceptable. No multiple-variable regression analysis was performed.

AUTHOR: **Stocks (1987)**

ENVIRONMENT: Jack pine stands in northeastern Ontario Canada. This study site is on level ground on stony humoferric podzols of glacial origin. The stand had 20 squ.meters/hectare basal area with an average DBH of 5cm. The forest floor consists primarily of feathermoss with some low understory shrubs of blueberry and sweet-fern. Stands were NOT logged or thinned and consisted primarily of jack pine.

STAND HISTORY: The stand was about 40 years old and resulted from a wildfire in 1948.

BURNING DETAILS: All units were broadcast burned using pneumatic flame throwers probably in strip headfires. Fires had rates of spread from 0.6-30.0 m/min and intensities of 291-40000 kW/m.

RANGE OF THE DATA: Preburn duff depths ran from 0.3-5.1 cm. Duff moisture codes went from 25-57. Buildup Indexes (BUI) ranged from 27-70. Depth of burn ranged from 1.9-5.5 cm. Regression equations derived from 13 observations.

COMMENTS: Equations use BUI as independent variable and this might not be useful. Study also includes slash and woody fuel consumption. Equations are not that good (R-square = 0.6) with predictions being + or - 0.5 cm depth of burn.

DUFF REDUCTION EQUATION SUMMARY

REGION: Pacific Northwest

AUTHOR: **Muraro (1971)**

ENVIRONMENT: Data was collected in 1964 in the King Fisher Creek drainage of the Interior west belt, Britsh Columbia, Canada. Units were on moderate slopes at 2800-3800 ft elevation on mostly southeast aspects. Site had good drainage and an annual precipiation of about 42 inches. Cover type was hemlock-cedar with western hemlock and red cedar comprising over 80% of boardfoot volume. Other species include western white pine and Douglas-fir.

STAND HISTORY: Stands were clearcut then logs were removed with tractor skidders. No treatment to the fuels is mentioned. Fuel loading of slash ran from 10-160 tons/acre. Fuel depths went from 1-4 feet. Nearly all predisturbance stands were oldgrowth hemlock-cedar.

BURNING DETAILS: Units were burned in July, August and September using strip headfires lit by unknown means.

RANGE OF THE DATA: Duff reduction (cm) DRC ranged from 1.5 to 3 cm, Duff moisture codes ranged from 10-30, duff depths ranged from 10 to 15 cm. Equations derived from 7 observations.

COMMENTS: I did the regression analysis for this paper using the raw data presented. The burns were not successful in reducing duff especially at these initial depths. I seems the duff moistures are high. Number of observations limiting.

AUTHOR: **Ottmar et al. (1985)**

ENVIRONMENT: Study sites in the Coastal Douglas-fir Zone with second growth western hemlock and Douglas-fir comprising the majority of the overstory. Some units were oldgrowth Douglas-fir forests with hemlock the understory species. Stands were located in the coastal and Cascade ranges in both Washington and Oregon on private and Forest Service lands.

STAND HISTORY: Stands were clearcut and cable-yarded. The cable yarding had up to 6 types of minimum piece size utilization standards.

BURNING DETAILS: The clearcuts were broadcast burned from May through September using strip headfires.

RANGE OF THE DATA: Preburn duff depths ranged from 3 to 17 cm. Large woody fuels went from 3-53% moisture contents with loadings of 3.9 to 53.9 tons/acre. Duff moisture contents ranged from 30 to 250%. Duff reduction (cm) DRC went from 1-6 cm. There were 43 observations.

COMMENTS: Most regression equations include variables not directly measureable before the burn (large fuel consumption).

AUTHOR: **Little et al. (1975)**

ENVIRONMENT: Study sites in the Coastal Douglas-fir Zone with second growth western hemlock and Douglas-fir comprising the majority of the overstory. Some units were oldgrowth Douglas-fir forests with hemlock the understory species. Stands were located in the coastal and Cascade ranges in both Washington and Oregon on private and Forest Service lands. These units are different than those used by Ottmar et al. (1985). Elevations ranged from 400-1400 m with slopes from 0-35%.

STAND HISTORY: Stands were clearcut and cable-yarded. The cable yarding had up to 4 types of minimum piece size utilization standards.

BURNING DETAILS: The clearcuts were broadcast burned from July through September using strip headfires.

RANGE OF THE DATA: Preburn duff depths ranged from 3 to 17 cm. Large woody fuels went from 3-55% moisture contents with loadings of 9-121 mg/ha. Duff moisture contents ranged from 16 to 310%. Duff reduction (cm) DRC went from 1-5 cm. Mineral soil exposed ranged from 0 to 35%. There were 38 observations.

COMMENTS: Most equations used preburn fuel moistures and loadings of large woody fuels for independent variables. The variable days since rain was also used. These variables may be unfeasible for management.

AUTHOR: **Amaranthus (1984)**

ENVIRONMENT: A soil scientist collected exposed mineral soil data after logging on steep slopes in the Siskiyou N.F. in southwest Oregon. Site was in the Douglas-fir zone and probably heavy to Douglas-fir but paper said forest was mixed evergreen. This study was initiated to determine how much mineral soil would be exposed after fire on steep slopes and would this mean additional erosion onsite.

STAND HISTORY: Little is printed on the history of the stand but the trees were havested by skyline techniques.

BURNING DETAILS: All units were broadcast burned probably using strip headfires. No detail as to burning conditions.

RANGE OF THE DATA: Percent exposed mineral soil (%) EMS ranged from 5-85%. Initial duff depths ranged from 0.5 to 3 cm. Equations derived from 16 observations.

COMMENTS: Data from a limited range of vegetation and site conditions. First stratification of data (spring/fall burn) divided the data set into two very small groups which might be too small for proper analysis. Regression analysis yielded equations with many independent variables further limiting the range of application.

AUTHOR: **Sandberg (1980)**

ENVIRONMENT: Study area was mostly the Cascade range in Washington and Oregon. This area was mostly in the Douglas-fir zone at elevations of 1000-4500 feet, slopes of 5-75% facing nearly all aspects. The units were primarily dominated by Douglas-fir.

STAND HISTORY: Stands were partial cut using skyline and maybe some tractor logging methods. Mature trees were probably second growth averaging around 40-50 cm on each of the units. No fuel treatment was mentioned.

BURNING DETAILS: Units were underburned in June thru Oct. using strip headfires with widths of 2-20 m set by drip torches. Flame lengths ranged from 0.15-3.7 m. Fuels in these units were lower than clearcut units (1-10 kg/sqm).

RANGE OF THE DATA: Fine fuel loadings went from 1.8-4.4 kg/sqm, duff reduction (cm) DRC ranged from 1.8-5.5 cm. Duff moisture content ranged from 20-270%. Initial duff depths ranged from 4.7-11.2 cm. NFDRS-1000 hr moistures ranged from 11-28%. Mineral soil exposed ranged from 0-65%. Equations derived from 13 observations.

COMMENTS: Most regression equations in this paper relate duff reduction and exposed min. soil to 1000 fuel parameters (moisture content and diameter reductions). These may or may not be useful to management. Thirteen cases do not allow for complete analysis. We should maybe add Sandberg+Little+Ottmar?

AUTHOR: **Blackhall and Auclair (1982)**

ENVIRONMENT: Study area was 40 kilometers southwest of Mcleod lake in central British Columbia, Canada. The soils were clays and sandy clay loams with a well defined gravel zone. Slopes were primarily flat at 2700 feet elevation. The stands were in the Subalpine Forest Zone with alpine fir, white spruce, and lodgepole pine comprising the majority of volume.

STAND HISTORY: Stands were logged during the winter using tractor skidding to remove logs from the site. The trees were probably mature subalpine forests.

BURNING DETAILS: Units were burned in June thru Aug. in the year following logging using strip headfires. Fine fuel moistures were 7-14% and large fuels were 9-30%. Winds ranged from 1-20 km/hr. Spread rates went from 0.6-19.3 m/sec.

RANGE OF THE DATA: Fine fuel loadings went from 0.6-2.5 kg/sqm, duff reduction (cm) DRC ranged from 2.8-8.4 cm. Duff moisture content ranged from 33-222%. Initial duff depths ranged from 3.8-12.9 cm. Slash loadings went from 3.4-10.3 kg/sqm. Mineral soil exposed ranged from 0-77%. Equations derived from 43 observations.

COMMENTS: Regression equations in this paper are strong (43 obs) and cover a wide variety of conditions normally found in the subalpine fir zone. Also include with duff reduction are slash reduction equations.

Appendix E

Equation dictionary for all algorithms in the model FOFEM

Equation Num.	Equation Form	Equation Reference
1	DRP = 97.1 - 0.519*LDM	EQU 9 Brown and others (1985)
2	DRP = 83.7 - 0.426*EDM	EQU 10 Brown and others (1985)
3	DRP = 114.7 - 4.20*NFDRSTH	EQU 13 Brown and others (1985)
4	DRP = 89.9 - 0.55*LDM	EQU 1 Harrington (1987)
5	DRC = 2.612 - 0.0225*LDM+0.417*PREDUFF	EQU 1 Brown and others (1985)
6	DRC=2.2380-0.0244*EDM+0.439*PREDUFF	EQU 3 Brown and others (1985)
7	DRC=4.503-0.267*NFDRSTH+0.399*PREDUFF	EQU 6 Brown and others (1985)
8	DRC=(37.37-0.75*LDM+21.19*PREDUFF/2.54)*2.54	
9	EMS=80.0-0.507*LDM: LDM<135	EQU 17 Brown and others(1985)
0	EMS=23.5-0.0914*LDM	EQU 19 Brown and others (1985)
1	EMS=167.4-31.6*LOG(EDM)	EQU 21 Brown and others (1985)
2	EMS=93.0-3.55*NFDRSTH	EQU 22 Brown and others (1985)
3	EMS=94.3-4.96*NFDRSTH	EQU 18 Brown and others (1985)
4	EMS=60.4-0.44*LDM	EQU 23 Brown and others (1985)
0	WRED1=(-0.602+0.89*WOOD1)/2.24	EQU 30 Brown and others (1985)
1	WRED10=(-0.602+0.89*WOOD10)/2.24	EQU 30 Brown and others (1985)
2	WRED100=(-1.501+0.845*WOOD100)/2.24	EQU 31 Brown and others (1985)
3	WRED1000=-2.7+0.79*WOOD1000	EQU 32 Brown and others (1985)
0	P=1.0/(1.0+EXP(-1.941+(6.32*(1.0-EXP(BT)))+0.000535*CK**2.0))	Ryan and Reinhardt (1988)

EPENDENT VARIABLES (Y-VARIABLES)

RC = Duff reduction in depth (cm)
[redacted] Duff reduction in percent (%)
[redacted] Exposed mineral soil (%)
[redacted] robability of mortality
RED1 = 1 hour woody fuel loading reduction (tons/acre)
RED10 = 10 hour woody fuel loading reduction (tons/acre)
RED100 = 100 hour woody fuel loading reduction (tons/acre)
RED1000 = 1000 hour woody fuel loading reduction (tons/acre)

DEPENDENT VARIABLES (X-VARIABLES)

DN = Lower duff moisture content (%)
DM = Average- entire duff moisture content (%)
REDUFF = Preburn duff depth (cm)
FDRSTH = Computed NFDR 1000 hr fuel moisture (%)
OOD1 = Preburn 1 hour woody fuel loading (tons/acre)
OOD10 = Preburn 10 hour woody fuel loading (tons/acre)
OOD100 = Preburn 100 hour woody fuel loading (tons/acre)
OOD1000 = Preburn 1000 hour woody fuel loading (tons/acre)
T = Bark thickness (in)
K = Crown scorched (%)